Senior Thesis

The Geology and Mineralogy of the Triassic Magnetite Deposits at Cornwall, Eastern Pennsylvania.

by
Patrick F. Bridgette
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Approved by:

Dr. Douglas Pride
Thesis Adviser

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Introduction

The Pennsylvania area is host to several significant copper-iron sulfide and magnetite deposits, not the least of which is the Cornwall magnetite deposit. Located one-half mile south of the town of Cornwall, PA, on U.S. Route 322 in the Appalachian mountains, this deposit is one of the oldest and most storied sources of iron ore in the United States, its recorded history as a mining district beginning well before the Revolutionary War and running to 1973 when easily accessible ore played out (Fig.1).

The mineralization was driven by the intrusion of a Triassic sill, into a heavily deformed Paleozoic limestone unit, related to Triassic rifting of the eastern margin of Laurentia. The dimensions of the deposit are approximately 30 m thick, 1300 m along strike, and 500 m down dip (Lapham and Gray,1972), giving a volume of 19.5 million meters cubed of ore body, which is equivalent to 90 million tons of iron ore This deposit became reknowned the world over and a model for this type of mineralization.

This paper will discuss the origin, mineralization, structure, stratigraphy, and history of the Cornwall mining district, with an emphasis on genesis and method of emplacement.

Figure 1: Geologic map of Pennsylvania with Cornwall area indicated

History

The magnetite mines at Cornwall were the oldest, continuously worked mines in the Western hemisphere (Lapham and Gray, 1959). The first discovery of iron is credited to Peter Grubb in 1732, whose father hailed from the ancient mining district of Cornwall in England, and hence Peter gave the name to this area. By 1742, Peter Grubb had added to his holdings by purchasing 442 acres in the vicinity of the discovery, which included three hilly outcroppings of iron, and he built a charcoal fired furnace. Upon his death in 1754, Grubb deeded his operations to his sons who oversaw the workings during the Revolutionary War. The company produced cannon, shot, and stoves for the Continental Congress, using captured Hessian soldiers as a cheap labor force (Lapham and Gray, 1972).

By 1864, through the vagaries and complications of inheritance, the original ownership of the mining area had been split 96 ways among various relatives and it was not until 1926 that the holdings were again consolidated when Bethlehem Steel Company purchased all 96 interests. Bethlehem operated the plant and its three eastern mines, down to a depth of 1225 feet, as well as the western open pit (largest open pit East of the Mississippi). All of the mines closed in 1973, ending 241 years of continuous mining in the region.

Previous Work

Theories concerning the origin of the magnetite deposits at Cornwall, and related deposits in the area, highlight the changes through time in the interpretation of mineral deposits. Early hypotheses of Rogers (1858) and Lesley and d'Invilliers (1886) proposed a source of iron from the remobilization of sedimentary limonite due to the heat of the intruding diabase. According to Rogers, the source for this iron was a nearby shale, but

Lesley and d'Invilliers proposed the iron was remobilized from the limestone that hosts the Cornwall deposit. Spencer (1908) invoked a source for the iron-bearing solutions within the diabase, a conclusion supported by Hickok (1933) and Hotz (1950,1953). Working at the nearby Dillsburg deposit, Hotz suggested that magnetite in these types of deposits originated by expulsion during a late pegmatitic-granophyric differentiation stage in the diabase. Kullerud and Yoder (1963), theorize that the magma phase of the diabase, particularly the olivine series silicates reacted with sulfur to release oxygen for the production of magnetite and/or hematite. Popovich (1964) asserted that silicification and mineralization were related to depletion of the diabase but that silicification, both spatially and genetically was more closely related to the *in situ* diabase sheets than the ore mineralization. The theories discussed above were challenged by Lapham and Gray (1959, 1961) and Lapham (1962,1968). Their theory of a distant common magmatic origin for both diabase and iron rather than *in situ* derivation of iron from a crystallizing diabase was championed by Sims (1968), although he was working on the related Morgantown deposit. In a broad study of the magnetite province, Davidson and Wyllie (1965,1968) suggested that the low-titanium magnetite of the region may possibly have been derived from a titanium-free late magnetite generated in the diabase by the alteration (oxidation) of ulvöspinel.The definitive work on the area was authored by Lapham and Gray (1972), and in this work they supported their earlier hypothesis on the origin of the deposit in addition to detailing the overall geology of the Cornwall region. Eugster and Chou (1979) concurred with the hypothesis by Lapham and Gray of a distal ore genesis, and proposed a "convection cell" model for the transport of iron-bearing fluids, discussed in detail below. Studies of the mineralogy and lithology of the Cornwall

mine were published by Robinson (1985), and Rose (1990) that are in general agreement with the theories of Lapham and Gray for the origin of the ores in the Cornwall region.

Structure and Stratigraphy

It should be noted that the Cornwall Mine (CM) is one of several magnetite deposits across eastern Pennsylvania (Fig. 2). These deposits are all related to a belt of Triassic diabase dikes and sheets that in turn is related to the Triassic rifting of the eastern margin of Laurentia. As shown in Figure 2 the magnetite ores of the various Pennsylvania districts all occur on the northern or southern edges of the Triassic rifts where diabase comes in contact with Paleozoic carbonate host rock (Eugster and Chou, 1979). To facilitate understanding of the structural and lithological controls on mineralization in the area, a brief description of stratigraphic units is essential and is given in Figure 3.

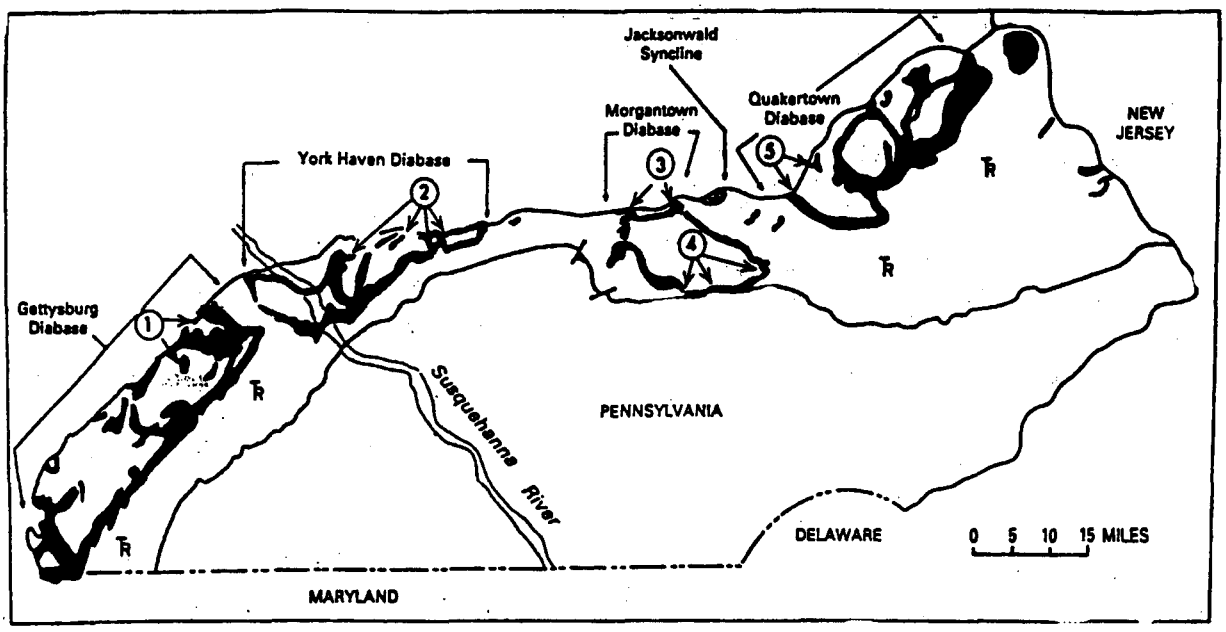
The host rock for the Cornwall deposit is intensely deformed and isoclinally folded Cambrian limestone. In the open pit of the western ore body of the CM, the ore sat atop the diabase sheet in a wedge shaped replacement of the Buffalo Springs Formation, capped by a wedge of Mill Hill Slate (Fig. 4). At its western limit, the body had a dip length of ~ 1600 ft., pinching out to the east. The strike length was ~ 4000 ft. with a maximum thickness of ~ 150 ft. The western ore body is structurally contained on its western margin by a rise in the diabase that terminates the host limestone, and on its eastern margin the limestone is cut out by Blue Conglomerate, which forms an irregular ore boundary (Lapham and Gray, 1972)

The eastern ore body, site of the three underground mines, is a lenticular, bean-shaped mass with a strike length of 2000 feet, a dip length of 2400 feet down dip, and an average thickness of 100 feet. As in the western pit, the footwall of the eastern mines is the diabase, but the hanging wall is either Mill Hill slate (up dip) or Blue Conglomerate (down dip). The ore in

both bodies always is separated from Triassic sediments by Blue Conglomerate, Mill Hill Slate or Buffalo Springs Formation (Gray and Lapham, 1959). It should be noted that a reverse fault separates the two ore bodies and its relationship to them probably did affect deposition due to the fact that the principle of cross cutting relationships suggests the faulting probably occurred after diabase intrusion but before ore formation.

Prior to the work of Lapham and Gray (1972), geologists in the region had problems assigning ages to the Mill Hill and Blue Conglomerate formations, as seen in Figure.3. Lapham and Gray tentatively gave the age as Ordovician but due to the complicated structure of the area, and the paucity of fossils, defining a relative age remains problematic (Fig.4). Both are local units and are thought to correlate with the Ordovician Martinsburg Formation.

As seen in Figure 4, the Buffalo Springs Formation lies both above and below the diabase. Below, the Buffalo Springs Formation and other Cambrian rock units are overturned, and above the diabase, ore replaces the Buffalo Springs Formation. One hypothesis for the occurrence above and below the ore bodies is that the Buffalo Springs Formation was faulted and offset prior to sheet intrusion, and the diabase intruded along this plane of weakness. However, there is no hard evidence for such a fault. Lapham and Gray (1972) suggested that the diabase 'rafted' or carried along part of the BSF on its journey, in an analogous fashion to a glacier plucking masses of rock from the terrain as it travels through.



Map of diabase-magnetite ore districts in the Pennsylvania Triassic belt (from Lapham and Gray, 1972, Pennsylvania Geological Survey Bulletin M-56, ser. 4, p. 281). 1, Dillsburg; 2, Cornwall, including, from west to east, Hummelstown, Carper, Cornwall, and Doner mines; 3, Wheatfield, including, from west to east, Wheatfield and Ruth mines, Fritz Island, and Esterly (in Jacksonwald syncline); 4, Morgantown-French Creek, including, from west to east, Morgantown, Jones, Hopewell, and French Creek mines; 5, Boyertown. All districts are now inactive.

Figure 2: Relationships of several magnetite deposits, Triassic diabase, and country rocks across Eastern Pennsylvania.

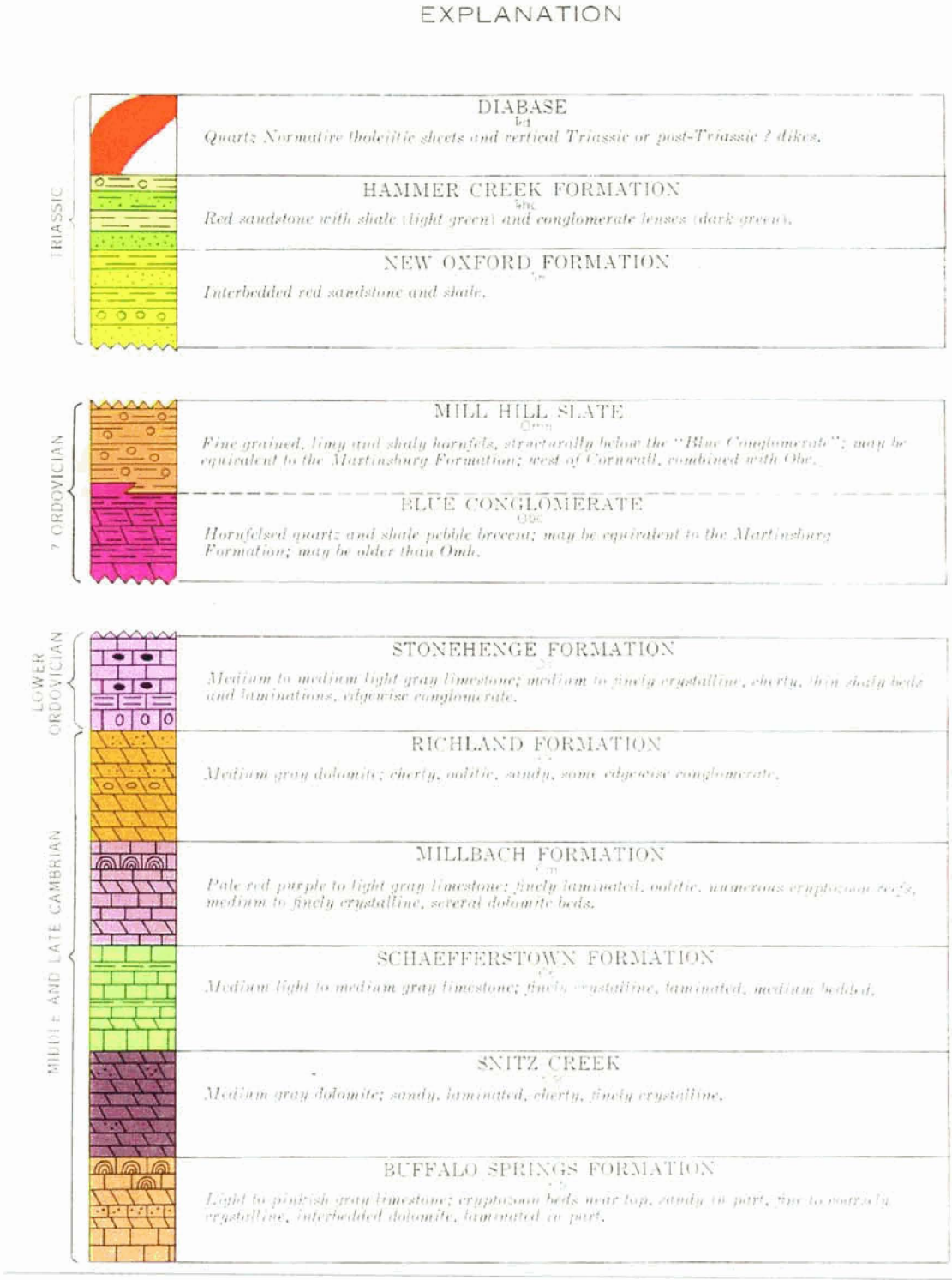


Figure 3: Stratigraphic column and Lithologic descriptions for Cornwall area.

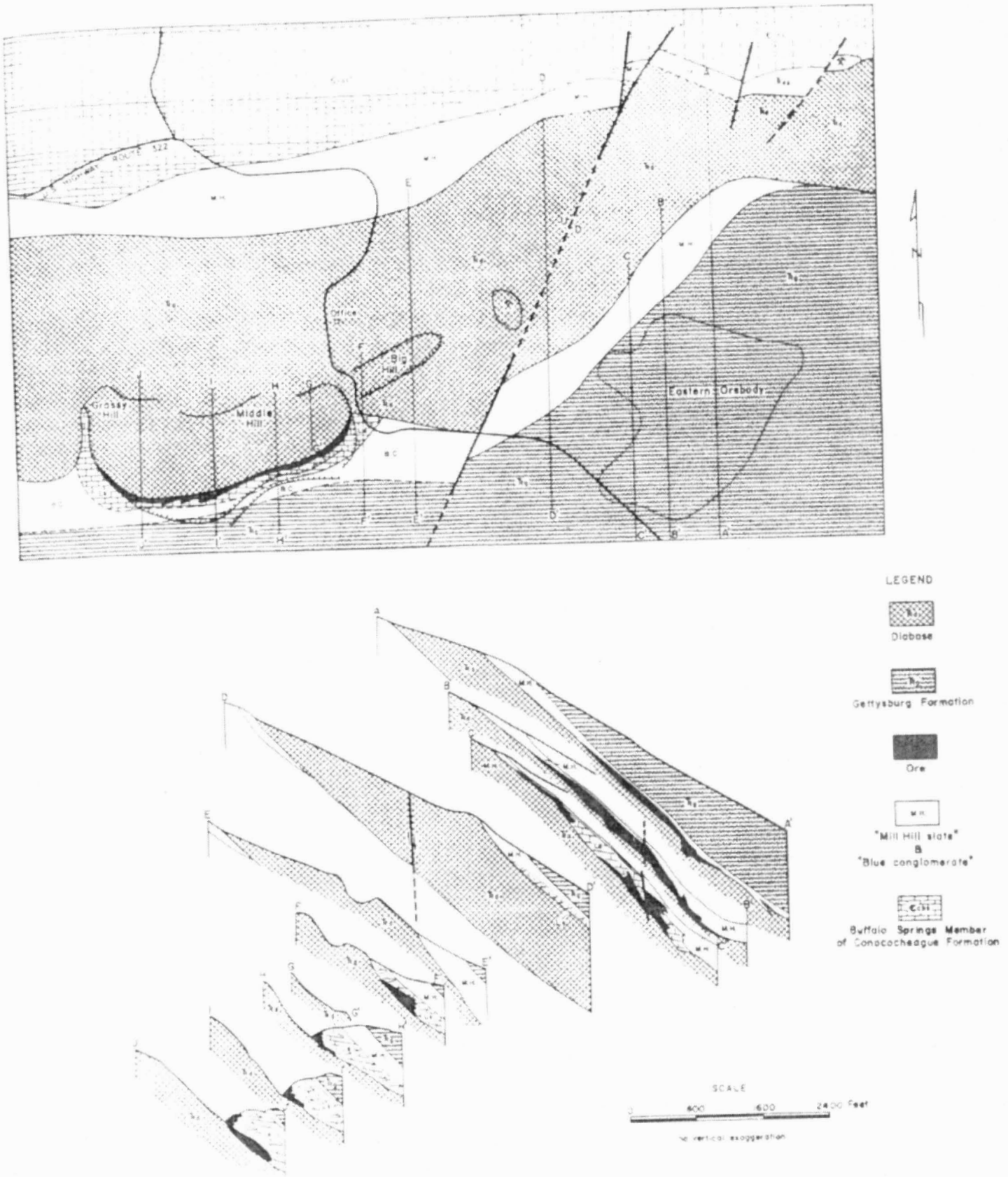


Figure 4: Geologic Map of Cornwall with selected cross sections.

Mineralogy

As mentioned, the most common ore mineral in the Cornwall deposit is magnetite. Other common metallic minerals are, in order of decreasing abundance, pyrite, chalcopyrite, and hematite. Accessory minerals include native copper, chalcocite, galena, sphalerite, covellite, bornite, pyrrhotite, and marcasite. The most common gangue minerals are calcite, orthoclase, actinolite, chlorite, quartz, and micas. In addition to these minerals, significant cobalt, gold, and silver have been refined from pyrite and chalcopyrite, and represented a very important by-product of the primary iron mining enterprise.

Magnetite: The Cornwall magnetite ranges in texture from granular-anhedral to octahedral and dodecahedral euhedral crystals. In reflected light, the former appear light gray and the latter is a darker gray. Davidson and Wyllie (1965) refer to these two colors as 'blue' and 'brown', respectively. The light gray magnetite is richer in iron than the dark magnetite, and may represent an earlier, purer form of the mineral prior to contamination of the iron-rich ore fluid by assimilation of country rock components during transport.

Throughout the Cornwall ore body, magnetite is observed to either replace completely or 'cap' hematite. The capping occurs primarily at the hanging wall and is thought to be a reduction and recrystallization feature, rather than a replacement of hematite by magnetite (Davidson and Wyllie, 1965).

On a macroscopic scale, magnetite occurs commonly in the Buffalo Springs Formation limestone. Here, the ore appears as alternating green and dark bands along the original sedimentary foliations of the country rock (Fig. 5 (I) and (Ia)). The magnetite

usually is associated with actinolite and chlorite, which display the green banding. During the life of the deposits, the Cornwall deposit produced approximately 90 million tons of iron ore that averages 40 percent iron. (Lapham and Gray, 1972)

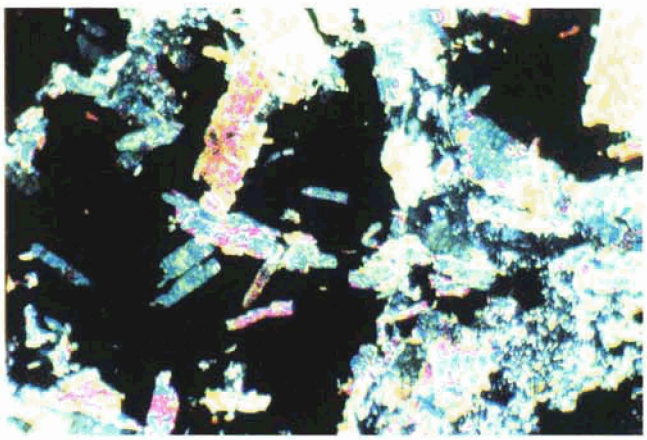
Pyrite: Pyrite is common throughout the Cambrian and Ordovician sediments of the Cornwall area and occurs as both cubic and composite crystals. The cubic variety appears commonly as limonite pseudomorphs, and the more complex variety occurs in veins that frequently transect magnetite ore. Pyritization spanned the time frame of ore deposition, often being replaced by chalcopyrite mineralization (Gray and Lapham, 1959). Although used as a source of sulfur for the production of sulfuric acid, pyrite is not in itself an important economic mineral. Its importance at Cornwall lies in the fact that it contains on average 1.3 percent by weight cobalt, and that it provides a suitable host for replacement by chalcopyrite, an important source of copper in the deposit. The high concentration of cobalt in the pyrite made the Cornwall mine the largest producer of cobalt in the country until the early 1950's (Robinson, 1988)

Chalcopyrite: This mineral usually occurs in large pockets and veins replacing pyrite and magnetite, and it frequently is associated with microcrystalline quartz (Fig. 5 (II)). Replacement tends to be along crystallographic planes and it often transects laminated bands of magnetite and actinolite/chlorite that are common in the Cornwall deposit (Lapham and Gray, 1972).In addition to copper, refinement of the chalcopyrite in the CM yields valuable quantities of gold and silver, and it is estimated that approximately 100,000 oz. of gold, and 750,000 oz. of silver were recovered during mining of the Cornwall ore bodies producing a significant source of byproduct income for the owners (G.R. Robinson, 1988)

Figure 5: Selected polished surfaces and thin sections of common ore minerals at Cornwall.

(I): Polished surface specimen displaying common appearance of much of the ore. Darker bands contain magnetite and actinolite, lighter bands consist of actinolite, chlorite, and mica. The banding follows the original laminations and foliations of the host rock. Note the vein of pyrite/chalcopyrite transecting the banding.

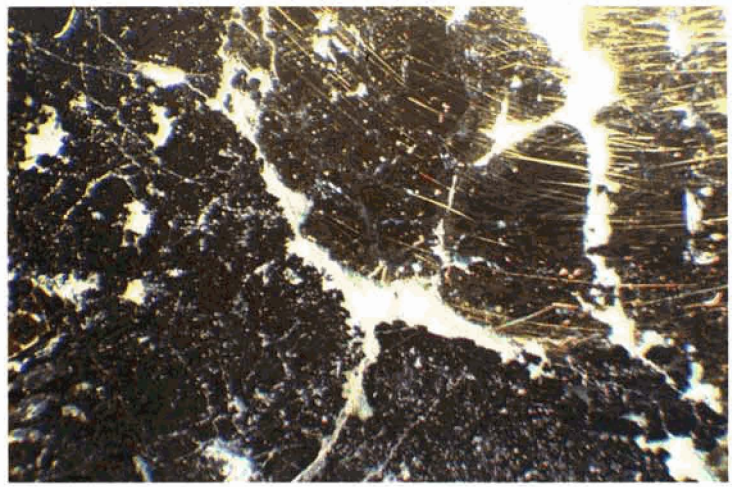
(6x magnification under oblique light. Photo taken on Kodak Tungsten E6 160 film on a WILD MP551 microscope.)



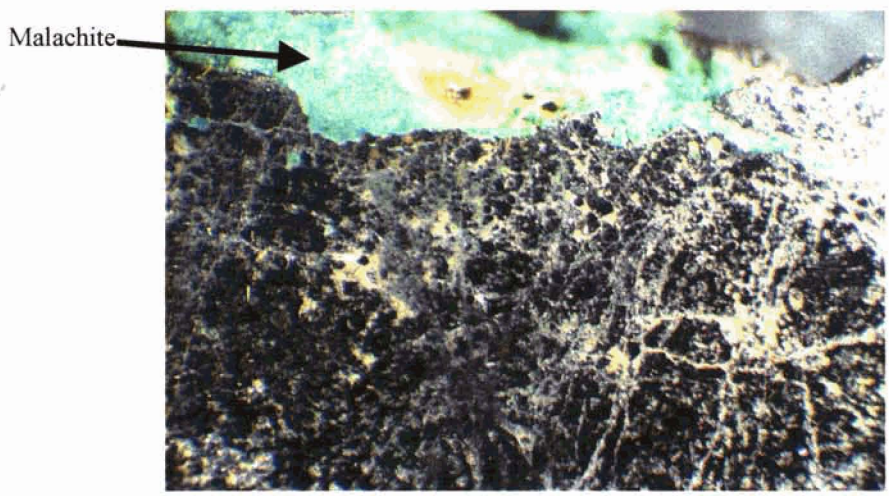
(I. a): Thin section of (I). The opaque areas are magnetite. Groundmass is actinolite and chlorite (anomalous blue colors). Note the embayment of magnetite by the later forming silicates.

(10x magnification under crossed nicols. Photomicrograph taken with Kodak Tungsten E6 160 film on a Leitz Ortholux II Pol-Bk microscope.)

Figure 5 continued.

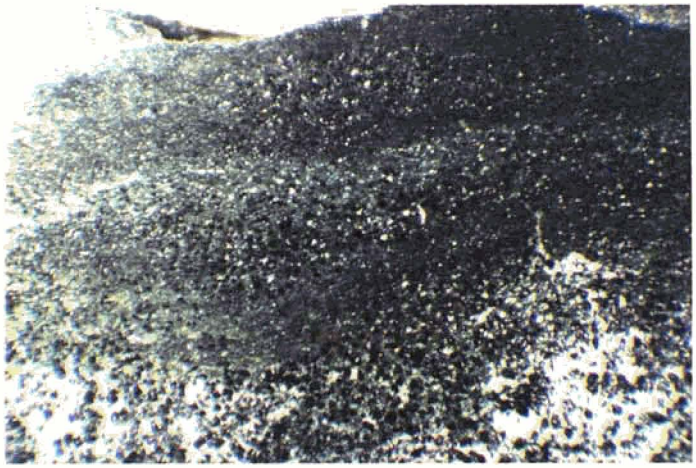


(II): Polished surface specimen of a vein of chalcopyrite (golden) replacing massive magnetite (black) . This is a common occurrence at Cornwall as is the accompaniment of chalcopyrite with microcrystalline quartz (white veins).
(6x magnification under oblique light. Photo taken on Kodak Tungsten E6 160 film on a WILD MP551 microscope.)

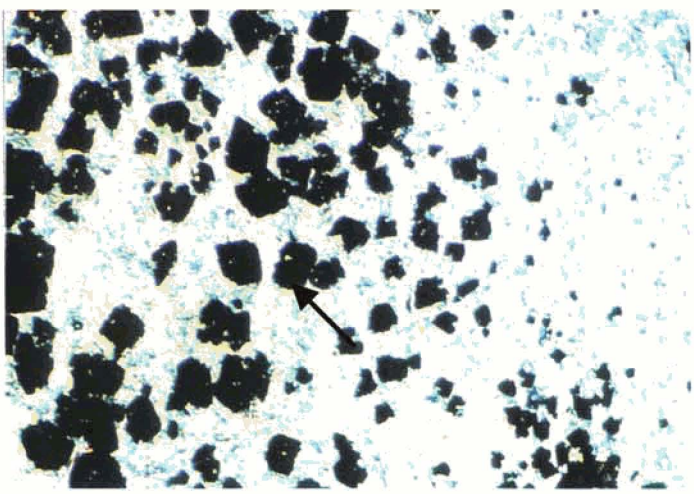


(III): Polished surface specimen of massive, black granular magnetite possibly derived from the reduction of specular hematite. Note the presence of green malachite, indicating oxidation at or near the surface.
(6x magnification under oblique light. Photo taken on Kodak Tungsten E6 160 film on a WILD MP551 microscope.)

Figure 5 continued.

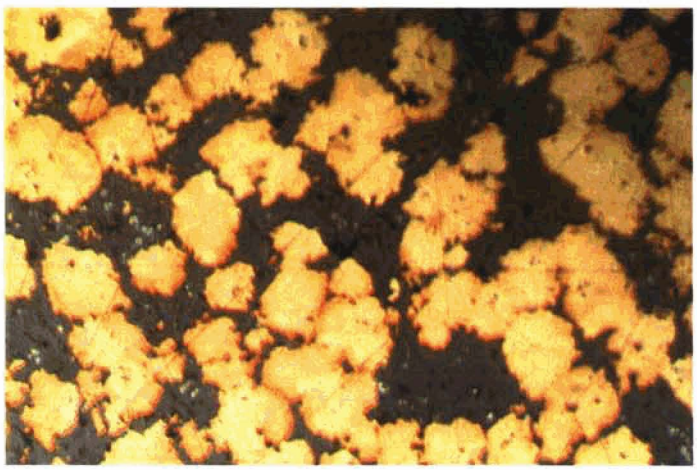


(IV): Polished surface sample of 'speckled' ore.The dark, granular masses are euhedral to sub-hedral crystals of magnetite in a matrix of actinolite, chlorite, and micas.
(6x magnification under oblique light. Photo taken on Kodak Tungsten E6 160 film on a WILD MP551 microscope.)

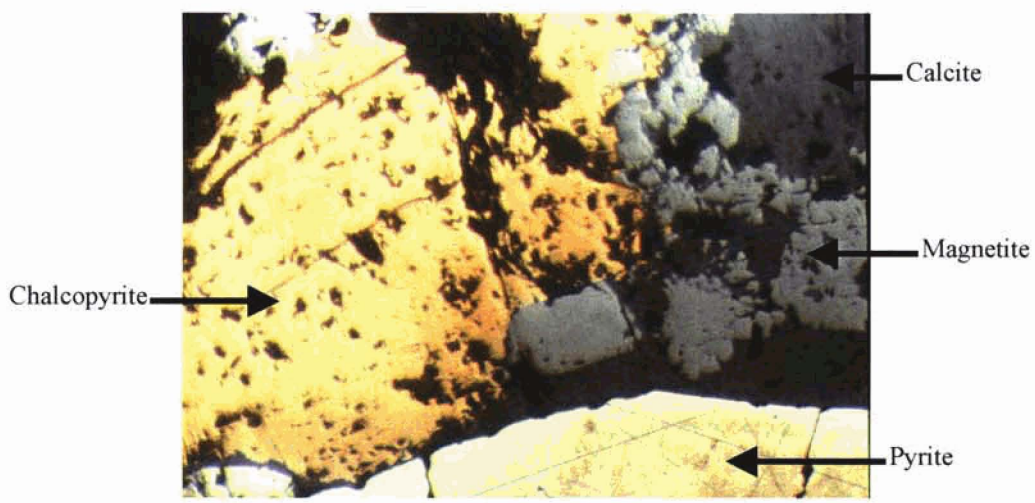


(IV, a): Thin section of same sample as above. Note the well developed crystal faces on the opaque magnetite.
(10x magnification under crossed nicols. Photomicrograph taken with Kodak Tungsten E6 160 film on a Leitz Ortholux II Pol-Bk microscope.)

Figure 5 continued



(V):Polished surface specimen of bright yellow 'blossoms' of chalcopyrite in a matrix of microcrystalline quartz. Striations on the chalcopyrite are due to polishing.
(10x magnification under incident light. Photo taken with Kodak Tungsten E6 160 film on a Leitz Ortholux II Pol-Bk.)



(VI): Polished surface specimen showing a closer view of the transecting vein in (I). Note the brecciated appearance of the crystals. Note the brecciated appearance of the crystals.
(10x magnification under incident light. Photo taken with Kodak Tungsten E6 160 film on a Leitz Ortholux II Pol-Bk.)

Genesis and Deposition of ore

The Cornwall deposit, like the other magnetite deposits in Pennsylvania, is a replacement of carbonates above a sheet of Triassic tholeiitic diabase. According to Robinson (1985), the critical features relating these deposits are: 1) diabase sheets of sufficient thickness to set up hydrothermal circulation of mineral rich solutions; 2) the presence of saline brines to carry metals (the presence of chlorides greatly increases the solubility of iron in 650 C water); 3) the presence of replaceable carbonate units in the proper geometry to hydrothermal circulation to buffer fluid pH and channel fluid flow; and an 4) external source of sulfur to cause sulfide deposition.

It would be true to say that the Cornwall deposit meets all of the above criteria, and with the only unknown being the source of the iron for the deposit. The obvious choice of source would be the country rock itself but chemical analysis of the Buffalo Springs, Mill Hill, and Blue Conglomerate formations show no meaningful depletion in iron content as the ore body is approached, and these rocks thus probably could not have made available the high volume of iron needed to produce the large Cornwall deposit. In addition, the movement of ore solution from such a source to the diabase and then into the rocks above is not a likely scenario (Lapham and Gray, 1972). The country rocks, as the name implies, provided a suitable host for ore deposition, but not the ore itself.

The next most obvious source of the iron in the Cornwall (and other) magnetite deposits is the diabase itself, but geologic evidence seems to argue such an origin. The diabase is offset by faulting but the ore is not, indicating that ore emplacement occurred after intrusion of the diabase and related contact metamorphism (Eugster and Chou, 1979). Lapham and Gray (1972, on p.247) state that: "There is no observational evidence for escape of iron from Cornwall

diabase", although they do note that compared to other diabases, the diabase at Cornwall is low in iron containing only about 7.4 percent.

Another source of ore was proposed by Kullerud and Yoder (1963) through the reaction of sulfur with silicates, particularly the olivine series, to produce oxygen for the formation of magnetite and hematite. Iron for such reactions comes naturally from the diabase magma that produced the intrusive sheet. These authors noted that only a few percent sulfur is all that is needed to convert the silicates and produce a typical assemblage of sulfide minerals and magnetite. The following is a sample of a typical reaction:

2Fa + 1S = 1FeS + 1Mag + 2Qtz;

3Fa + 2S = 2FeS + 2Hem + 3Qtz.

(Fa = fayalite; Mag = Magnetite; Hem = Hematite; Qtz = Quartz.)

This process could account for the general lack of olivine in the diabase and the presence of iron sulfide and magnetite. Such a source for the ore, however, is unlikely because the unaltered diabase adjacent to the Cornwall deposit contains only about 0.03 percent sulfur. This is far less than would be required to alter significant volumes of olivine. (Lapham and Gray, 1972, p.245)

Lapham and Gray (1972) favor a source for the iron (and oxygen) in the Cornwall deposit 'at depth'. This hypothesis requires the presence of a "primary magma" that gave rise to both the diabase and the iron-rich solution, as separate events. The faulting of the diabase presented a conduit for iron-rich solutions from depth to circulate through and interact with the reactive host rocks.

The latter hypothesis is in agreement with the method of ore deposition suggested by Eugster and Chou (1979). In their model, the driving force for the ore solution was a convection cell with the 'hot' end of the cell at depth and the 'cold' end being the Buffalo Springs formation host rock (Fig. 6). As mentioned previously, iron is far more soluble in the presence of chlorides than when merely in a chloride-free supercritical fluid. At depth, HCl is formed by the conversion of muscovite to K-feldspar, and iron in the melt reacts with the HCl to form iron chlorides. The iron chlorides ride the convection current to the 'cold' end of the cell where they come into contact with the calcium carbonate of the BSF. This reaction precipitates magnetite and enriches the solution in calcium chloride and carbon dioxide, some of which may return to the 'hot' end, helping to fuel the cycle. It should be noted that this model requires that much of this carbon dioxide escape to the surface, as high concentrations of carbon dioxide would have an adverse effect on the solubility of the iron chlorides, thereby slowing or stopping ore formation and emplacement.

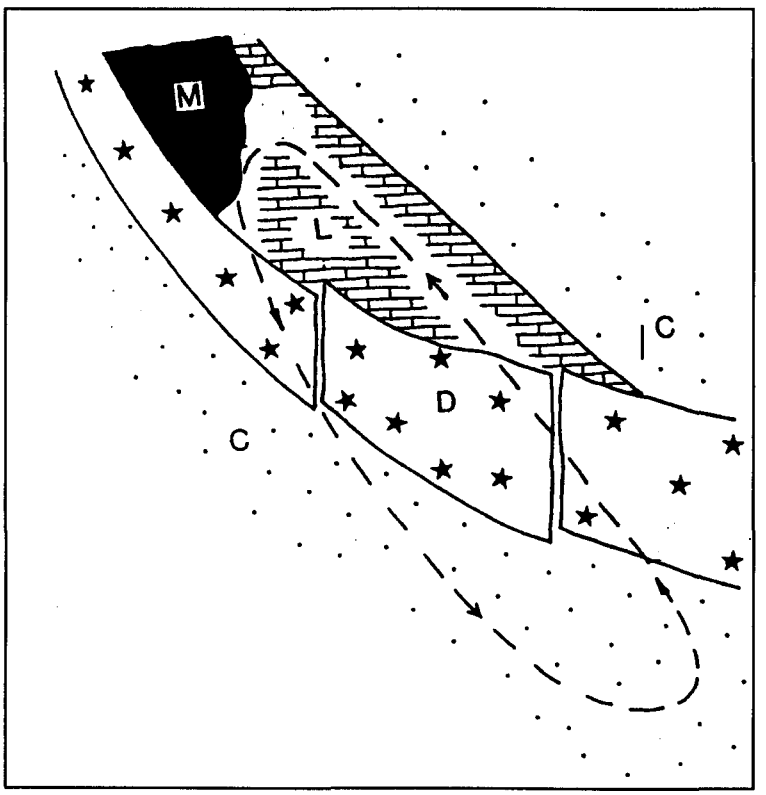


Figure 6: Schematic sketch of hydrothermal convection cell model.
(M = magnetite, L = limestone, D = diabase, C = country rock.)

Conclusion

The Cornwall magnetite deposit most definitely is a metasomatic, hydrothermal deposit formed by the replacement of Cambrian-aged, metamorphosed, and folded limestone host-rock. The ore at Cornwall is a consequence of the Triassic rifting and related volcanics that were part of the incipient break-up of eastern Laurentia. The igneous activity in the vicinity of the Cornwall and related deposits was manifested as diabase sheets. The sheer volume of iron in the CM is not directly a result of the diabase intrusion, although it is indirectly related to that igneous event. Lacking any reasonable nearby source for iron in the host sediments, or in the (iron-poor) diabase, the only probable source of iron is at depth within the igneous system that generated the diabase.

Ore emplacement at Cornwall and formation of the diabase intrusion are separate events that were related to a single, primary magmatic source. First, the tholeiitic sheet was injected and subsequently cooled and fractured. Second, iron from this same magma was mobilized in a chloride-rich solution and transported via a conduit provided by the fracturing and faulting of the diabase into contact with the carbonate country rock producing the classic skarn deposit that has become known as the Cornwall magnetite deposit.

The driving mechanism for mobilization of the iron-rich hydrothermal solution from depth was in all probability a convection cell. The cell was set up by temperature differences that cycled the hydrothermal solutions from a hot, deep source to the cooler host rock, and back to depth.

Regardless of where the iron came from or how it got there, the Cornwall magnetite deposit is truly impressive in its sheer size. In addition to producing iron, copper, cobalt, silver,

and gold to several important industries, the deposit itself has been studied in detail and has yielded considerable data on the formation of large-scale skarn-type deposits.

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